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Comparing Simulated and Measured Soil Organic Carbon Content of Clay Soils for Time Periods Up to 60 Years

KENNETH N. POTTER
USDA-ARS
Grassland Soil and Water Research Laboratory
808 East Blackland Road
Temple, Texas 76502, USA

STEVEN R. POTTER
Texas A&M Experiment Station
808 East Blackland Road
Temple, Texas 76502USA**,**

JAY D. ATWOOD
USDA-NRCS
808 East Blackland Road
Temple, Texas 76502,USA**,**

JIMMY R. WILLIAMS
Texas A&M Experiment Station
808 East Blackland Road
Temple, Texas 76502, USA

ABSTRACT / The Erosion Productivity Impact Calculator model (EPIC) was recently altered to include algorithms based upon concepts found in the Century model with the exception of a daily time step. We compared measured soil organic carbon (SOC) content values with simulated values to validate the new EPIC simulation model carbon sequestration routine. The simulations were based upon detailed soils data for three clay soils (Udic Haplusterts) and actual weather data recorded near the sample sites. Historical cropping systems for central Texas were simulated for a period of 120 years, the period from the original breaking of the native prairie sod to modern times. In addition, the effect of tilling the soil for 60 or more years and then returning the site to grass was simulated. Periods of restored grass were 6, 26, and 60 years. It was necessary to adjust a parameter, the fraction of humus in the passive pool, to make realistic simulations. Once adjusted, EPIC simulated the decline in SOC with agriculture well at all three sites in central Texas. EPIC also simulated the relative difference in SOC content occurring between continuously tilled sites and sites with restored grass well.

Increasing attention is being given to the accumulation of carbon dioxide, a potential greenhouse gas, in the earth's atmosphere, and to the potential for global warming from the consequent greenhouse effect. Carbon dioxide is increasing in the atmosphere, partly from the combustion of fossil fuels and from changes in land use from forest and range ecosystems to agriculture. Soils comprise a vast reservoir of organic carbon (Batjes 1996) that is potentially amenable to management by the selection of appropriate management strategies. Tillage effects on soil organic carbon (SOC) contents have been studied for a considerable period (Whiteside and Smith 1941). In a review of soil management studies, Mann (1986) showed that SOC decreases rapidly with initial tillage, but then the rate of decrease declines in a nonlinear manner and gradually approaches a new, lower equilibrium. More recently, studies have been directed toward the potential increase in SOC with no-till management practices and the interaction of management with climate (Potter and others 1998, Powlson and others 1998).

KEY WORDS: Carbon sequestration; Simulation modeling; EPIC

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The recent concern about global warming has led to attempts to determine both the total worldwide carbon stocks available (Batjes 1996) and to estimate the effects of management on sequestration of carbon in soil (Kern and Johnson 1993). The Conservation Reserve Program (CRP) has also stimulated interest in the potential of returning soils to grassland or forest management practices to store more soil carbon. Gebhart and others (1994) reported that CRP land sequestered SOC at a rate of 1.23 t C ha^{-1} yr^{-1} for the initial 5 years after returning agricultural land to grass. However, it is doubtful that this rate can be sustained. Just as soils eventually arrive at a new equilibrium for SOC with tillage, carbon sequestration will also eventually approach a new equilibrium after reestablishment of grass vegetation.

Long-term studies of management practices are relatively few and limited in the scope of the soil and climatic properties studied. Simulation modeling is likely to be the best method of estimating management effects on soil properties for a wide range of soil and climatic conditions. However, in order to be considered realistic in their predictions, simulation models must be verified against real-world data. The Erosion Productivity Impact Calculator model (EPIC), although originally designed to quantify erosion effects on soil productivity (Williams and others 1984), has been continuously updated and refined into a model capable of describing management effects on soil and crops. Recently, concepts and some equations from the Century model (Parton and others 1987, 1993, and 1994), were used to develop a new carbon and nitrogen transformation submodel for EPIC. Although the new submodel runs on a daily time step, it should not be confused with the Daycent model (Parton and others 2001). Climatic, soil moisture, and temperature routines that previously existed and have been extensively tested in EPIC are used to drive the new EPIC soil carbon submodel.

The objective of our study is to compare measured and simulated amounts of SOC for soils managed for 120 years, from pristine native grasslands to modern agricultural soils. Modeling the effect of tillage and then returning the soils to grass for 6, 26, and 60 years will provide a unique test of the EPIC model to simulate potential carbon sequestration.

Materials and Methods

Three areas in central Texas were identified as having sites with a unique combination of management histories, i.e., a pristine never-tilled native prairie site, an agricultural site that has a long history of inversion tillage, and a previously tilled site that had been returned to grass.

Two areas are near Temple, Texas, one with a 6-year-old restored grassland (designated the Temple site), and a site with a 26-year-old restored grassland (designated the Burleson site). The third site, with 60-year-old restored grassland, is located near Riesel, Texas (designated the Riesel site). The three locations are within 75 Km of each other. Mean annual temperature for all locations was 19.5°C. Average rainfall was 878 mm yr^{-1} for the Temple and Burleson locations and 908 mm yr^{-1} for the Riesel locations.

Soils at all of the sites are Vertisols with large montmorillonitic clay content in the soil profile. Soils at the Temple location were the Houston Black clay (Udic Pellusterts). The 6-year restored grassland was sown to Switchgrass (*Panicum virgatum* L.) in 1992. The Temple native prairie was predominately Indiangrass (*Sorghastum nutans* (L.) Nash), Little Bluestem (*Schizachyrium scoparium* (Michaux) Nash), and Johnsongrass (*Sorghum halepense* (L.) Pers.), with some Giant Ragweed (*Ambrosia trifida* L.) present.

The soils at the Burleson locations were classified as Houston Black clay at the native prairie and as Branyon clay (Udic Pellusterts) at the grass and agricultural sites. The 26-year restored grassland vegetation was predominately Indiangrass, Little Bluestem, Switchgrass, Big Bluestem (*Andropogon gerardii vitman* var. gerardii), and Sideoats grama (*Bouteloua curtipendula* (Michaux) Torrey). The native prairie vegetation was predominately Little Bluestem and Indiangrass. The less diverse nature of the native prairie vegetation indicates that the site may have been overgrazed at some time in the past.

The soils at the Riesel location were classified as Houston Black clay soils. The 60-year restored grassland vegetation was predominately King Ranch Bluestem (*Bothriochloa ischaemum* var. songarica), Little Bluestem, Indiangrass, and Switchgrass. The native prairie vegetation was predominately King Ranch Bluestem, Little Bluestem, with a strong influence of Giant Ragweed.

Description of Field Studies

Seven cores, 4 cm in diameter, were obtained from each site. Soils were sampled to a depth of 1.2 m. Cores were segmented to obtain depth increments of 0 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 30, 30 to 40, 40 to 60, 60 to 80, 80 to 100, and 100 to 120 cm. Soil segment wet weight was determined. The soil core was then split lengthways. Half of the soil core segment was weighed, oven dried at 105°C for 48 hours, and the dry weight was recorded. The soil water content was determined and used to correct the segment weight for calculating soil bulk density. The other half of the soil core was air dried until it easily crumbled and easily identified organic matter such as roots, stems, leaves, and plant crowns were removed. The remaining soil was crushed to pass a 2-mm sieve. A subsample of the cleaned soil sample was ground in a rolling grinder (Kelley 1994) in preparation for carbon analysis. The ground sample was oven dried for 3 hours at 65°C before burning.

Soil organic carbon was determined using a CR12 Carbon Determinator (LECO Corporation, Augusta, GA, USA) on samples of about 1 g (Chichester and Chaison 1991). Soil samples were burned at 575°C and carbon dioxide (CO_2) concentration in the airflow was determined with a solid-state infrared detector. The CO_2 concentration was integrated over the duration of the burn to determine the sample carbon concentration. Total mass of SOC and nitrogen were determined by multiplying the concentration times the soil bulk density.

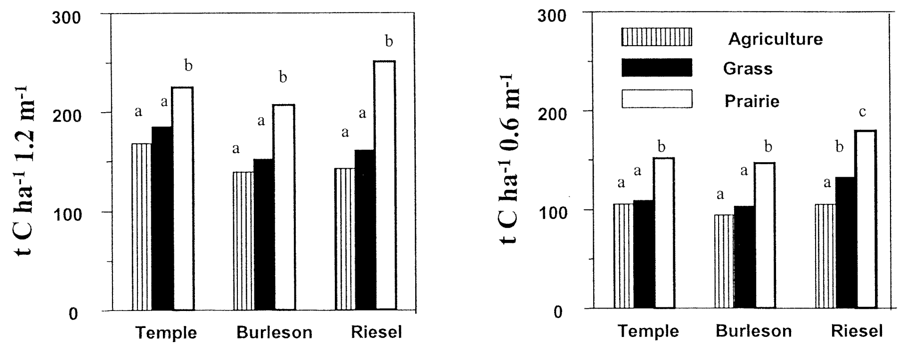

Figure 1. Measured organic carbon occurring in the surface 1.2 m of three soils in central Texas (from Potter and others 1999).

Input Data and Model Initialization

Daily rainfall and maximum and minimum air temperatures for the period from 1940 to 1999 collected at ARS Laboratories at Temple and Riesel, Texas were input for conducting the simulations. Data from 1880 to 1939 were unknown and were simulated by repeating the weather from 1940 to 1999. Other needed weather parameters were generated by the EPIC weather generator.

Historical management information was obtained from Richardson (1993) and the agricultural census (Alexander and Smith 1990). The period from 1880 to 1939 was assumed to have large amounts of inversion tillage, no fertilizer inputs, and a cotton (*Gossypium hirsutum* L.)–corn (*Zea mays*)–cotton crop rotation. A corn crop was simulated from 1940 to 1999, with increasing plant populations and fertilizer inputs over time. Corn populations and fertilizer rates were: 30,000 plants ha^{-1} and 4 kg N ha^{-1} and 2 kg P ha^{-1} for years 1940 to 1954; 40,000 plants ha^{-1} and 40 kg N ha^{-1} and 8 kg P ha^{-1} for years 1955 to 1969; 50,000 plants ha^{-1} and 66 kg N ha^{-1} and 10 kg P ha^{-1} for years 1970 to 1984; and 60,000 plants ha^{-1} and 86 kg N ha^{-1} and 11 kg P ha^{-1} for years 1985 to 1999. The grass was simulated as mixed range grasses with no fertilization. Initial soils data were approximated as being similar to the pristine native prairie sites reported by Potter and others (1999).

Results and Discussion

Intensive agricultural practices and resulting erosion and organic carbon oxidation have resulted in large losses in SOC in the agricultural soils as compared with the pristine native prairie sites (Figure 1). Simulation results showed a rapid decline in SOC after the transition from native prairie to agricultural production, as predicted by Mann (1986). However, the decline continued for an extended period, nearly 60 years, before a decrease in the rate of organic carbon reduction was apparent. Measured and simulated soil carbon was similar in the tilled agricultural soils, although the difference was greater at the Riesel site compared to the other two sites (Table 1). After 120 years of simulated tillage, loses of SOC were 34% at the Burleson site, 31% at the Temple site, and 47% at the Riesel site in the surface 1.2 m. This compared favorably with measured organic carbon losses of 33% at the Burleson site, 25% at the Temple site, and 43% at the Riesel site (Potter and others 1999).

Table 1. Simulated and measured amounts of soil organic carbon in the surface 0.6 m of the soil profile with continuous tillage

Site	Measured soil organic carbon (t ha^{-1})	Simulated soil organic carbon (t ha^{-1})
Temple	105.5	106.7
Burleson	94.4	90.1
Riesel	105.3	87.5

With the establishment of grasses and lack of tillage, measured organic carbon contents in the grass sites, although not significantly greater, were numerically larger than that in the agricultural sites (Figure 1) (Potter and others 1999). The organic carbon mass in the restored grassland was always intermediate between the agricultural site and native prairie site. Trends were most apparent in the surface 0.6 m, with SOC mass increasing with longer length of time in grass.

Simulation results showed similar trends, with increasing differences in SOC content between the agricultural soils and those with grass (Figure 2). Differences between grassed and tilled soil carbon content were similar in both the measured and simulation results (Table 2). There appears to be a trend for larger differences between measured and simulated results at longer time increments. However, the difference between the management systems in the simulation re-

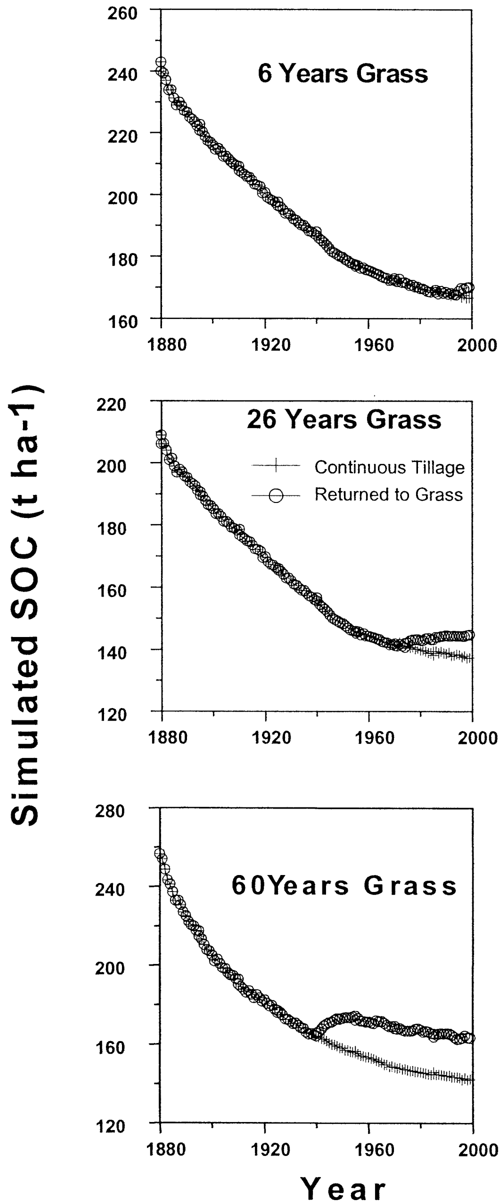

Figure 2. Simulated organic carbon in three soils with continuous tillage and after reversion to grass.

sults appeared to result from two separate causes. First, the tilled soils continued to lose some organic carbon, albeit at a much reduced rate compared to that occurring in the initial years of agriculture. Second, the grassed areas increased in carbon content rather rapidly for the first 10 years, but then reached relatively steady carbon content. Additional work is needed to determine whether the rapid increase in carbon content is reasonable or whether one should expect carbon to continue to increase over a longer period. Simulation results indicated that one possible reason for the plateau effect is caused by a lack of available nitrogen.

Table 2. Measured and simulated difference in soil organic content between returning to grass and continuous tillage for the surface 0.6 m

Site	Measured difference (t ha^{-1})	Simulated difference (t ha^{-1})
Temple	3.5	3.5
Burleson	8.5	8.0
Riesel	27.0	24.2

Initial simulation results with the new EPIC subroutine were disappointing, because simulated losses of soil carbon were greatly overestimated compared to measured values. This was partially caused by simulating simplified management practices that did not account for increases in plant populations and increasing amounts of fertilization over the past 60 years. The greatest effect, however, appears to be related to a parameter in the model that is defined as the fraction of humus in the passive pool (FHP in the EPIC code). We optimized this parameter to a value of 0.8 for the clay soils simulated in our study by comparing simulated and measured soil organic carbon content in the Temple agricultural soils. After defining FHP, the simulation results were greatly improved at the other sites and with other management practices. It may be that FHP is related to soil texture. Experimental results have shown that soil clay content can affect soil carbon levels. Usually carbon increases with increased clay content (Burke and others 1989). In any event, the poor initial simulation results support the comparison of measured and simulated data to ensure that results of simulations are meaningful.

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